Date: ____________________

Name: ____________________

ID: ____________________

LABORATORY
EXPERIMENT
NO. 6

POWER FLOW BETWEEN TWO SOURCES

OBJECT

1. To observe reactive power flow when sender and receiver voltages are different, but in phase.
   To observe real power flow when sender and receiver voltages are equal, but out of phase.
3. To study the flow of real and reactive power when sender and receiver voltages are different and out of phase.

DISCUSSION

Transmission lines are designed and built to deliver electric power. Power flows from the generator (sender end) to the load (receiver end) but, in complex interconnected systems, the sender and receiver ends may become reversed. Power in such a line may flow in either direction depending upon the system load conditions which, of course, vary throughout the day. The character of the load also changes from hour to hour, both as to *kVA* loading and as to power factor. How, then, can we attempt to understand and solve the flow of electric power under such variable conditions of loading, further complicated by the possible reversal of source and load at the two ends of the line?

We can obtain meaningful answers by turning to the voltage at each end of the line. In *Fig. 6-1* a transmission line having a reactance of *X ohms* (per phase) has voltages E_1 and E_2 at each end. If we allow these voltages to have any magnitude or phase relationship, we can represent any loading condition we please. In other words, by letting E_1 and E_2 possess any values and any relative phase angle, we can cover all possible loading conditions which may occur.

Referring to *Fig. 6-1*, the voltage drop along the line is $(E_1\text{-}E_2)$; consequently, for a line having a reactance X, the current I can be found by the equation.

$$I = \frac{E_1 - E_2}{X}$$

(A transmission line is both resistive and reactive, but we shall assume that the reactance is so much larger that the resistance may be neglected).

If we know the value of E_1 and E_2, and the phase angle between them, it is a simple matter to find the current I, knowing the reactance X of the line. From this knowledge we can calculate the real and reactive power which is delivered by the source and received by the load.

Suppose, for example, that the properties of a transmission line are as follows:

Line reactance per phase = *100 ohms*

Sender voltage = *20kV*

Receiver voltage = *30kV*

Receiver voltage lags behind sender voltage 26.5 degrees.

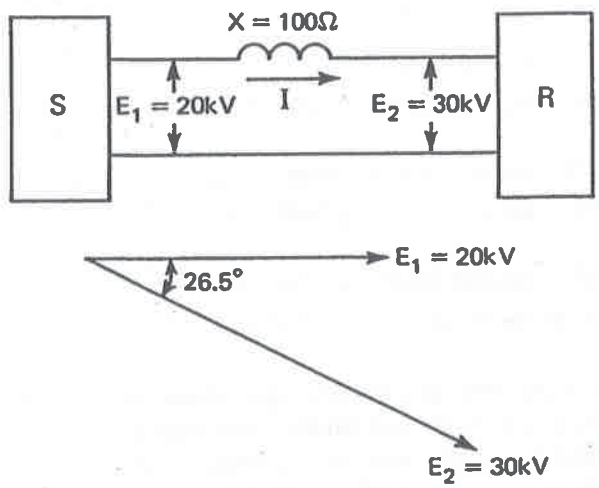

Fig. 6-2

These line conditions are represented schematically in *Fig. 6-2*. From the phasor diagram, on *Fig. 6-3*, we find that the voltage drop $(E_1\text{-}E_2)$ in the line has a value of *15kV*. The current I has a value of $15kV/100\Omega = 150A$ and it lags behind $(E_1\text{-}E_2)$ by 90 degrees. From the geometry of the figure, we find that the current leads E_1 by 27

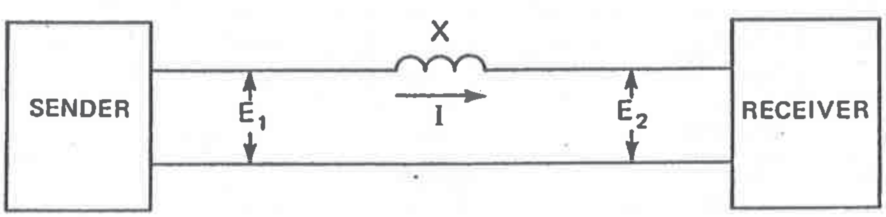

Fig. 6-1

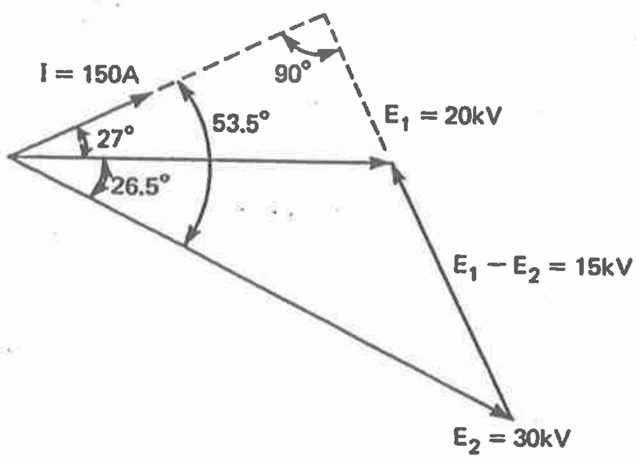

Fig. 6-3

degrees. The active and reactive power of the sender and the receiver can now be found.

Real Power delivered by the sender =
150A X 20kV X cos (−27°) = +2670kW.

Real Power received by the receiver =
150A X 30kV X cos (−53.5°) = +2670kW.

Reactive Power delivered by the sender =
150A X 20kV X sin (−27°) = −1360kvar.

Reactive Power received by the receiver =
150A X 30kV X sin (−53.5°) = −3610kvar.

Note: When determining the sine and cosine of the angle between voltage and current, the current is always chosen as the reference phasor. Consequently, because E_1 lags behind *I* by 27 degrees, the angle is negative.

Based upon the results calculated above, if wattmeters and varmeters were placed at the sender and receiver ends they would give readings as shown in *Fig. 6-4*. This means that active power is flowing from the sender to the receiver, and owing to the absence of line resistance, none is lost in transit.

However, reactive power is flowing from receiver to sender and, during transit, *(3610-1360) = 2250kvar* are consumed in the transmission line. This reactive power can be checked against *Line kvar* $= I^2X = 150^2 \times 100 = 2250$*kvar.* It will be noted that this is not the first time that we have found real power and reactive power flowing simultaneously in opposite directions.

REACTIVE POWER

When the voltages at the sender and receiver ends are in phase, but unequal, reactive power will flow. The direction of flow is always from the higher voltage to the lower voltage.

Consider a transmission line in which the voltage at the sender and receiver ends are *30kV* and *20kV* respectively and the line reactance is *100 ohms (Fig. 6-5).*

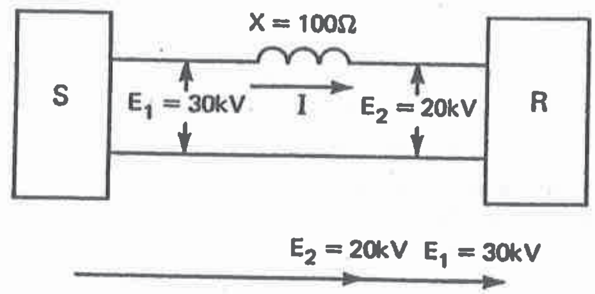

Fig. 6-5

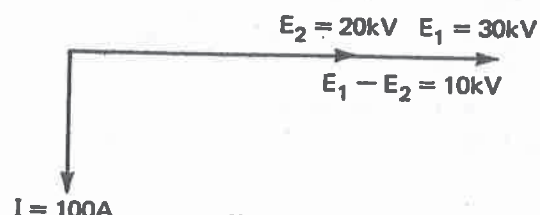

Fig. 6-6

The voltage drop in the line is *10kV*, and the current is *10kV/100 = 100A* as shown in *Fig. 6-6.*

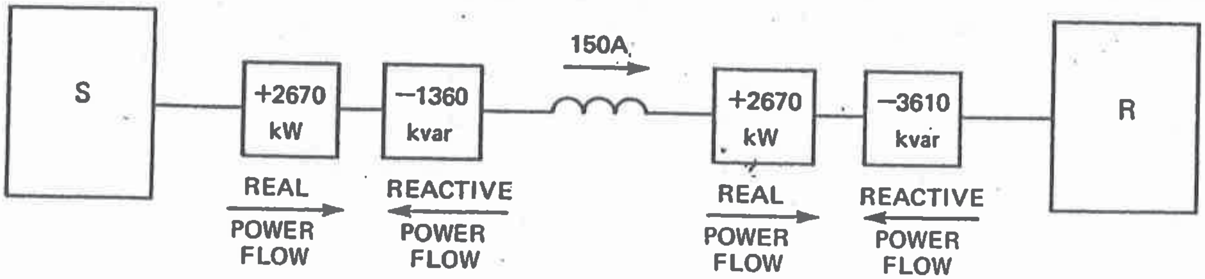

Fig. 6-4

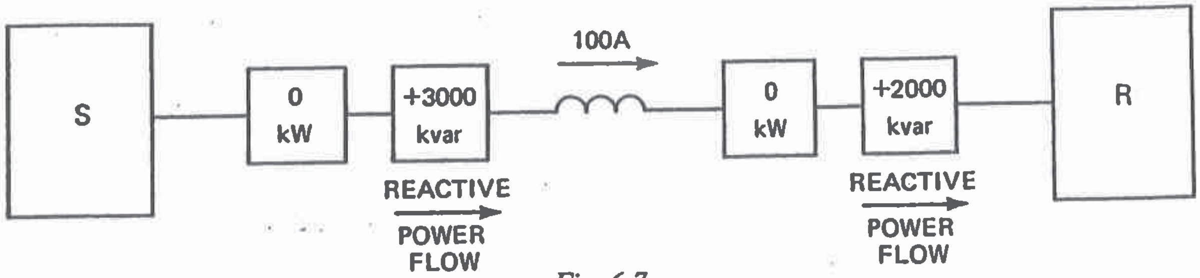

Fig. 6-7

The real power delivered by the sender end = $100A \times 30kV \times \cos(+90°) = 0W$.

The real power received by the receiver = $100A \times 20kV \times \cos(+90°) = 0W$.

The reactive power delivered by the sender end = $100A \times 30kV \times \sin(+90°) = +3000kvar$.

The reactive power received by the receiver = $100A \times 20kV \times \sin(+90°) = +2000kvar$.

If wattmeters and varmeters were placed at each end, the readings would be as shown in *Fig. 6-7.*

Reactive power flows from the sender to the receiver, and *100kvar* are absorbed in the transmission line during transit. As can be seen, reactive power flows from the high-voltage to the low-voltage side.

REAL POWER

Real power can only flow over a line if the sender and receiver voltages are out of phase. The direction of power flow is from the leading to the lagging voltage end. Again, it should be noted that this rule applies only to transmission lines which are principally reactive.

The phase shift between the sender and receiver voltages can be likened to an electrical "twist", similar to the mechanical twist which occurs when a long steel shaft delivers mechanical power to a load. Indeed, the greater the electrical "twist" the larger will the real power flow become. However, it is found that it attains a maximum when the phase angle between the sender and receiver ends is 90 degrees. If the phase angle is increased beyond this (by increased loading) it will be found that *less* real power is delivered.

Consider a transmission line in which the voltages at each end are equal to *30kV* and the receiver voltage lags behind the sender by 30 degrees. The line reactance is *100 ohms,* and the circuit is shown in *Fig. 6-8.*

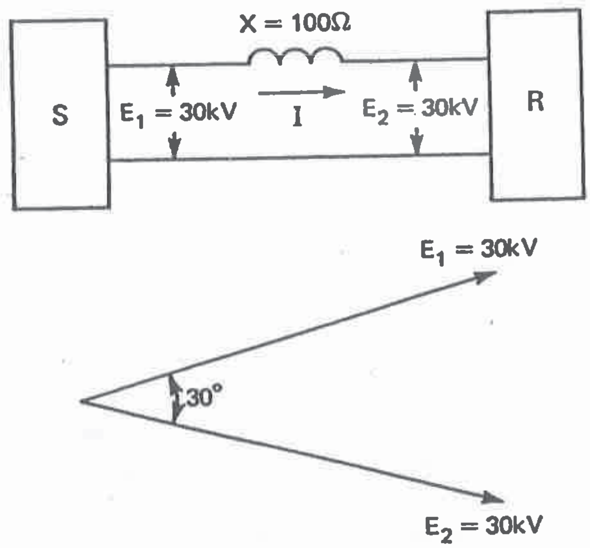

Fig. 6-8

The voltage drop in the line $(E_1\text{-}E_2)$ is found to be *15.5kV,* so the current $I = 15500/100 = 155A$ and lags 90 degrees behind, as shown in *Fig. 6-9.*

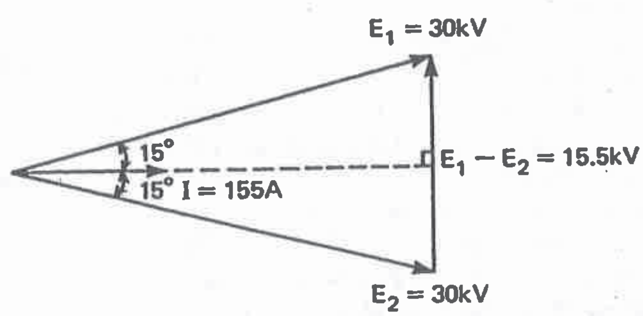

Fig. 6-9

Taking the current as the reference phasor, we can find the real and reactive power associated with the sender and the receiver end.

SENDER END

Real Power delivered =
$30kV \times 155A \times \cos(+15°) = +4500kW$.

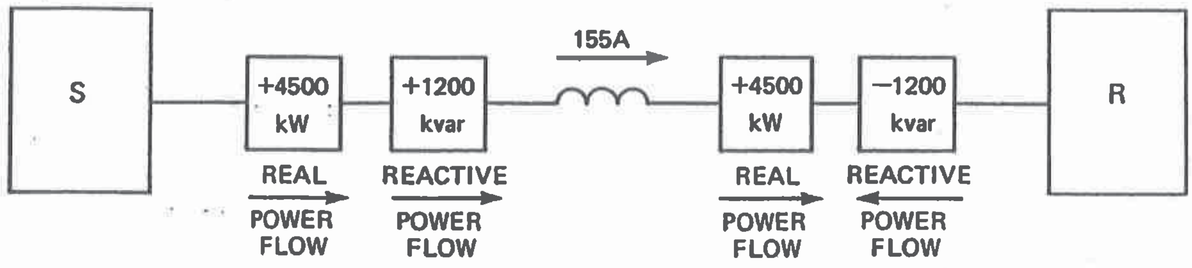

Fig. 6-10

Reactive Power delivered =
$30kV \times 155A \times \sin(+15°) = +1200kvar.$

RECEIVER END

Real Power received =
$30kV \times 155A \times \cos(-15°) = +4500kW.$

Reactive Power received =
$30kV \times 155A \times \sin(-15°) = -1200kvar.$

The sender delivers both active and reactive power to the line and the receiver absorbs active power from it. However, the receiver *delivers* reactive power to the line, so that the total reactive power received by the line is *2400kvar.*

This example shows that a phase shift between sender and receiver voltages causes both real and reactive power to flow. However, for angles smaller than 45° the real power considerably exceeds the reactive power.

INSTRUMENTS AND COMPONENTS

Power Supply Module (2) *(120/208V 3ϕ 0-120/208 3ϕ)*	*EMS 8821*
Resistance Module	*EMS 8311*
Inductance Module	*EMS 8321*
Three-Phase Transmission Line Module	*EMS 8329*
Capacitance Module	*EMS 8331*
Three-Phase Buck-Boost and Phase Shift Transformer Module	*EMS 8349*
AC Metering Module *(250V/250V)*	*EMS 8426*
Three-Phase Watt-Varmeter Module (2) *(300W-300var)*	*EMS 8446*
Phase Angle Meter Module	*EMS 8451*
Connection Leads	*EMS 9128*

EXPERIMENTS*

Caution: High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

In order to convey a sense of realism to the terms "sender" and "receiver" two consoles manned by two student groups will be used in the following experiments. A transmission line will connect the two consoles (Station A and B) and the active and reactive power flow between them will be studied. The experiment will be conducted in three parts.

1) Sender and Receiver voltages unequal, but in phase.
2) Sender and Receiver voltages equal, but out of phase.
3) Sender and Receiver voltages unequal, and out of phase.

SENDER AND RECEIVER VOLTAGES UNEQUAL BUT IN PHASE

☐ 6-1) Connect a three phase transmission line between the terminals 4, 5, 6 (variable AC output) of two consoles, one of which is designated as station A and the other, station B. Connect wattmeters, varmeters, voltmeters at each end as well as a phase angle meter as shown schematically in *Fig. 6-11.*

☐ 6-2) With the transmission line switch *S* open, set the line-to-line voltages $E_1 = E_2 = 180V$ and observe that the phase angle is zero between terminals 4-5 of station A and terminals 4-5 of station B. (If the phase angle is not zero, see Experiment 2-8.

Phase angle is zero: ☐ *yes* ☐ *no*

☐ 6-3) Without making any changes, measure the phase angle between terminals 4-5 of station A and terminals 5-4 of station B.

Phase angle = ... ☐ *(lag)* ☐ *(lead)*

☐ 6-4) Without making any changes, measure the phase angle between terminals 4-5 of station A and terminals 5-6 of station B.

Phase angle = ... ☐ *(lag)* ☐ *(lead)*

* These experiments may be carried out by two collaborating groups.

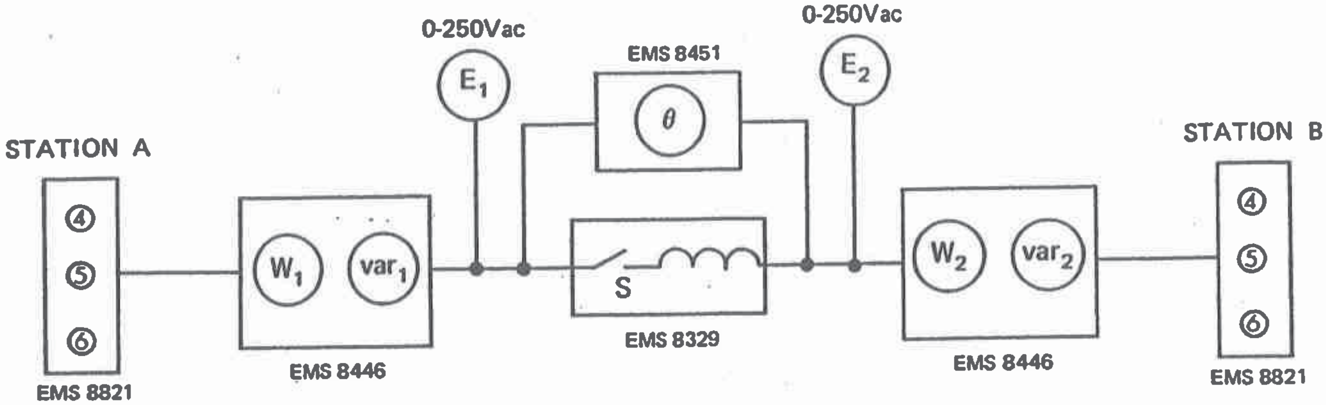

Fig. 6-11

☐ 6-5) Measure the phase angle between terminals 4-5 of station A and terminals 6-4 of station B.

Phase angle = ... ☐ *(lag)* ☐ *(lead)*

☐ 6-6) By measuring all phase angles between line and neutral of station A and B prove that the phasor diagram for both stations is as given in *Fig. 6-12.*

The purpose of this preliminary phase angle check is to familiarize ourselves with the phase angles between the voltages at the two stations.

☐ 6-7) Close the transmission line switch; with $E_1 = E_2 = 180V$, and the transmission line impedance = *60 ohms*, observe the watt-varmeter readings. There should be no significant power exchange.

W_1 = ...

W_2 = ...

var_1 = ...

var_2 = ...

☐ 6-8) Raise station A voltage to *200V* and observe power flow.

W_1 = ...

W_2 = ...

var_1 = ...

var_2 = ...

Which of the two stations would be considered to be the sender? ....

☐ 6-9) Reduce station A voltage to *160V* and observe power flow.

W_1 = ...

W_2 = ...

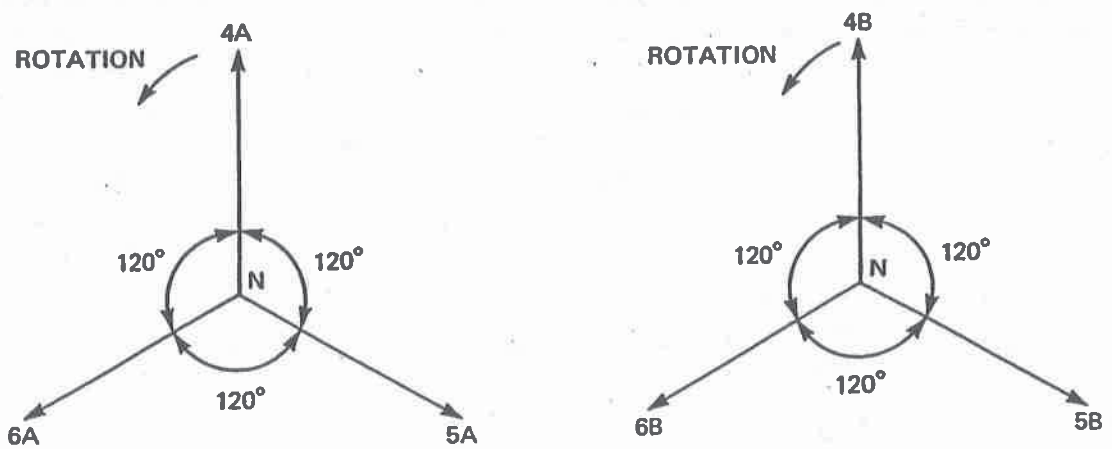

Fig. 6-12

var_1 = ...

var_2 = ...

Which station would be considered to be the sender? ....

☐ 6-10) Vary the voltage of both station A and station B and check the truth of the statement that reactive power always flows from the higher voltage to the lower voltage.

SENDER AND RECEIVER VOLTAGES EQUAL BUT OUT OF PHASE

A phase shift transformer *(EMS module 8349)* will be used to shift the phase of station A by 15 degrees. The phase shift (lag or lead) is obtained by changing the connections of a three-phase transformer by means of a tap-switch. The manner in which this is accomplished is explained in greater detail in Experiment 11; for our purposes it is sufficient to know that when the position of the tap-switch is altered, the secondary voltage will either a) be in phase with the primary, b) lag the primary by 15 degrees or, c) lead the primary by 15 degrees.

☐ 6-11) Connect the phase-shift transformer to fixed AC terminals 4, 5, 6 of station A. Adjust voltage at stations A and B to 208 V, with the phase angle meter, determine the phase angle of the secondary voltage 4, 5, 6 with respect to variable AC terminals 4, 5, 6 of the power supply of station B (see *Fig. 6-13*). Record your readings for the three positions of the phase-shift tap-switch in *table 6-1*.

Note: The buck-boost tap-switch must be kept at zero and the correct phase sequence must be applied to the primary of the transformer.

☐ 6-12) Check that the phase-shift is the same for all three phases, and that all voltages are balanced.

TAP SWITCH POSITION	PHASE ANGLE (LAG/LEAD)	E_1 (V)	E_2 (V)
0°			
+15°			
−15°			

Table 6-1

☐ 6-13) Connect a three-phase, *120 ohm* transmission line between secondary terminals 4, 5, 6 of the phase shift transformer and power supply terminals of station B *(See Fig. 6-14)*. After inserting watt-varmeters at each end of the line, change the tap-switch position of the phase-shift transformer and record your results in *Table 6-2*.

Does this experiment bear out the statement that real power flows from the leading towards the lagging voltage side of a transmission line? ....

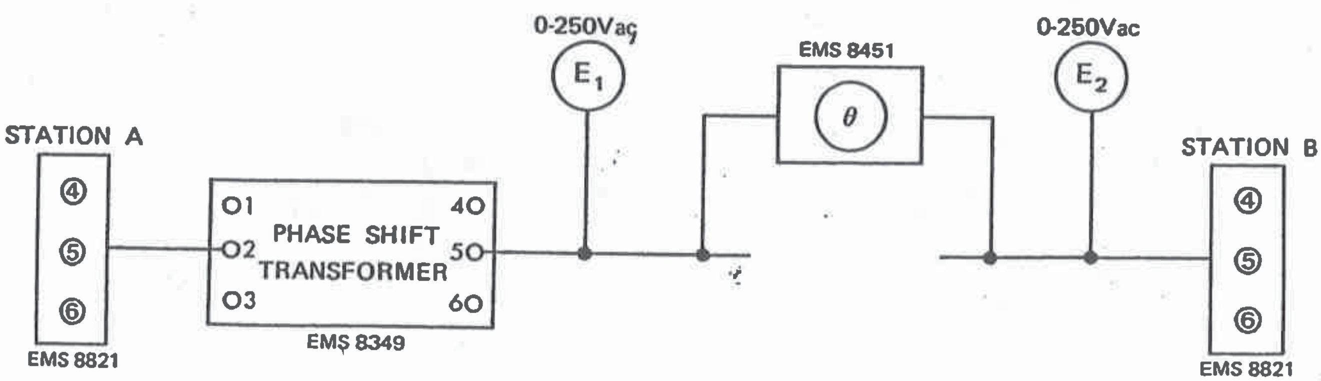

Fig. 6-13

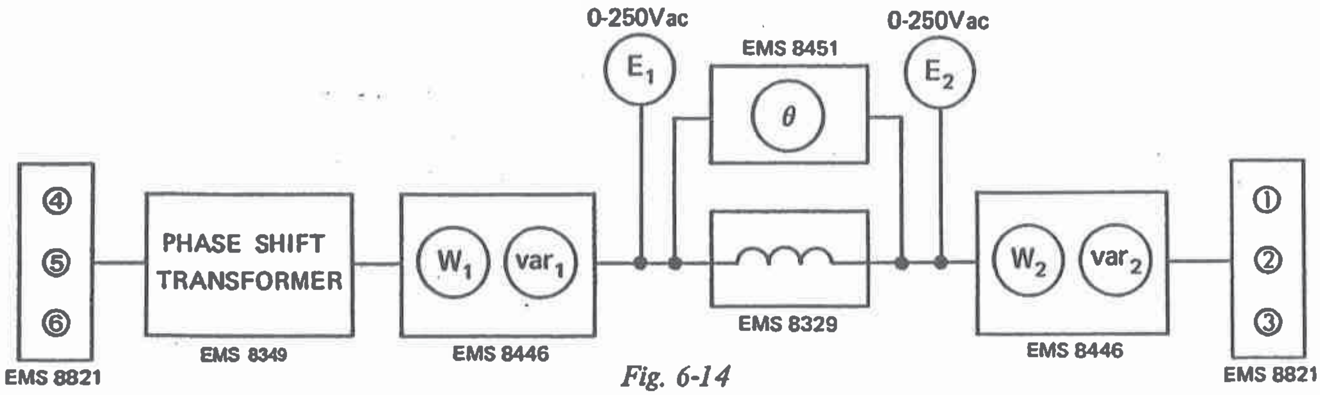

Fig. 6-14

TAP SWITCH POSITION		E_1 (V)	W_1 (W)	var_1 (var)	E_2 (V)	W_2 (W)	var_2 (var)	PHASE ANGLE (°)
EXP. NO. 6-13	0°							
	+15°							
	−15°							

Table 6-2

QUESTIONS AND PROBLEMS

1. A three-phase transmission line has a reactance of *100 ohms* and at different times throughout the day it is found that the sender and receiver voltages have magnitude and phase angles as given in *Table 6-4*.

In each case calculate the real and reactive power of the sender and receiver and indicate the direction of the power flow. The voltages given are line-to-line.

E_S (kV)	E_R (kV)	PHASE ANGLE	SENDER		RECEIVER	
			MW	Mvar	MW	Mvar
100	100	60° E_S leads E_R				
120	100	60° E_S leads E_R				
100	120	60° E_S leads E_R				
120	100	30° E_S lags E_R				
120	100	0°				

Table 6-4

2. In Problem 1 assume that $E_s = E_r = 100kV$ at all times but that the phase angle between them changes in steps of 30° according to the *Table 6-5*. Calculate the value of the real power in each case as well as its direction of flow, knowing that E_r lags E_s in each case.

Plot a graph of real power vs phase angle on *Fig. 6-16.*

Is there a limit to the maximum power which such a line can deliver under the static voltage conditions? ....

θ	MW SENDER	MW RECEIVER
0°		
30°		
60°		
90°		
120°		
150°		
180°		

Table 6-5

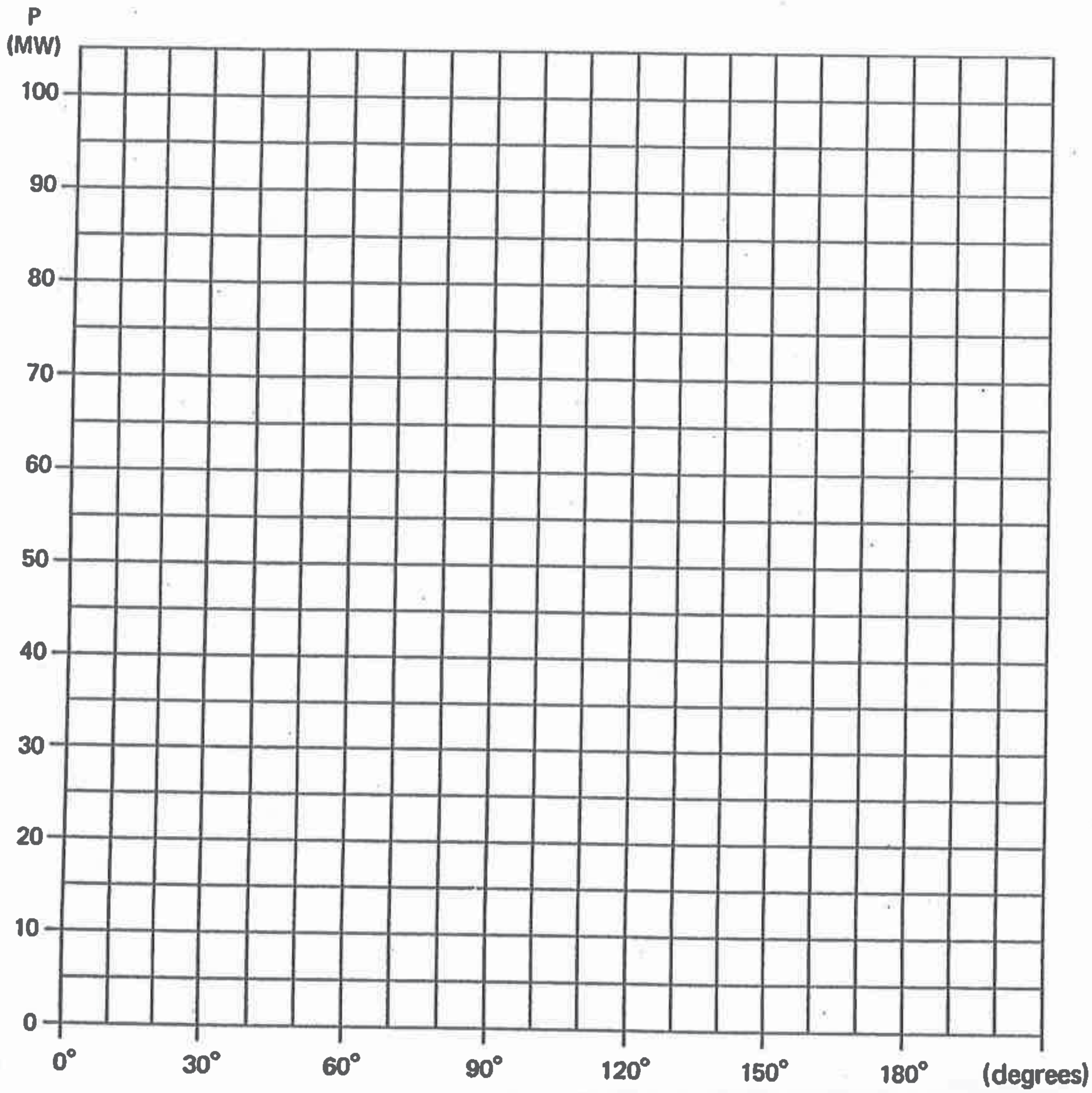

Fig. 6-16